Sub-Wavelength Analog Optical Delay Lines

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DARPA/MTO Analog Optical Signal Processing Kick-Off Meeting

Sheraton San Diego Hotel and Marina
San Diego, California

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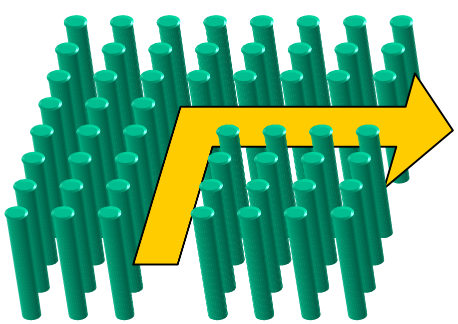

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The SWAODL* Approach

- **Use of low-loss InP-based serpentine waveguide to give:**
  - **delays on order of 3 ps $\rightarrow$ 10 nsec**
  - **path lengths of 100 cm $\rightarrow$ 5 m on 1 cm^2 chip size**
- **"Programmable" taps utilizing resonant InP-micoring resonators, tuned by bias.**
- **Development of ultra-low loss InP waveguides (α<0.1 cm^{-1}) and tight-bend radius structures (r<10 μm).**

**Sub-Wavelength Analog Optical Delay Lines*

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SWAODL Conceptual Overview

Need: $Q>10^6$ as demanded by RF channelization.
Approach: Low-loss resonantly coupled InP microring resonators.

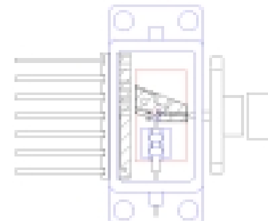
Need: Time delay of 10 nsec (~3 meter aperture).
Approach: InP-based serperntine waveguide structure with r<10 μm.

Need: Semiconductor propagation loss < $0.1\ cm^{-1}$.
Approach: Low material overlap waveguide structures (ridge and/or photonic “airguide”).

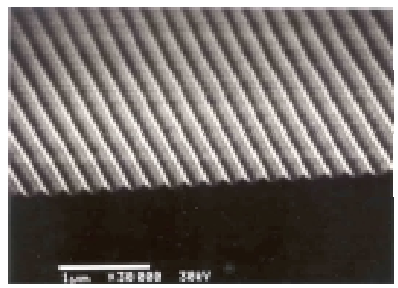
Sarnoff Photonics: Examples

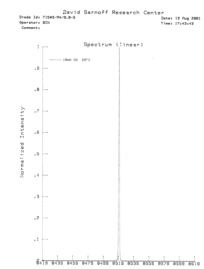
Low-Capacitance Gain Element

High-speed device packaging

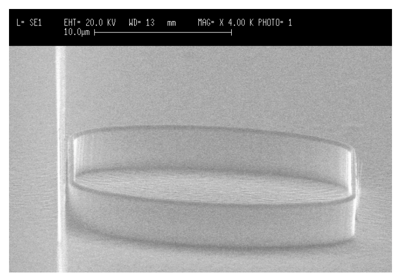


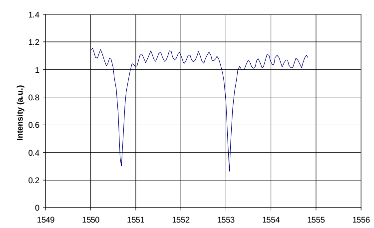
Narrow linewidth DFBs





Resonant Modulators





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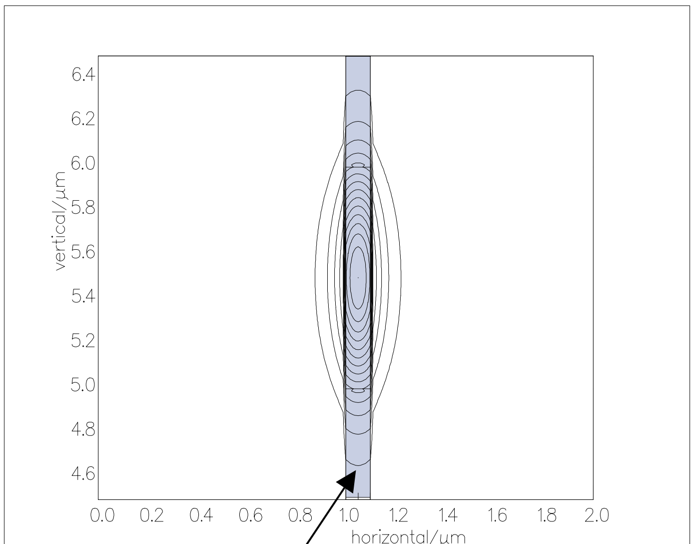
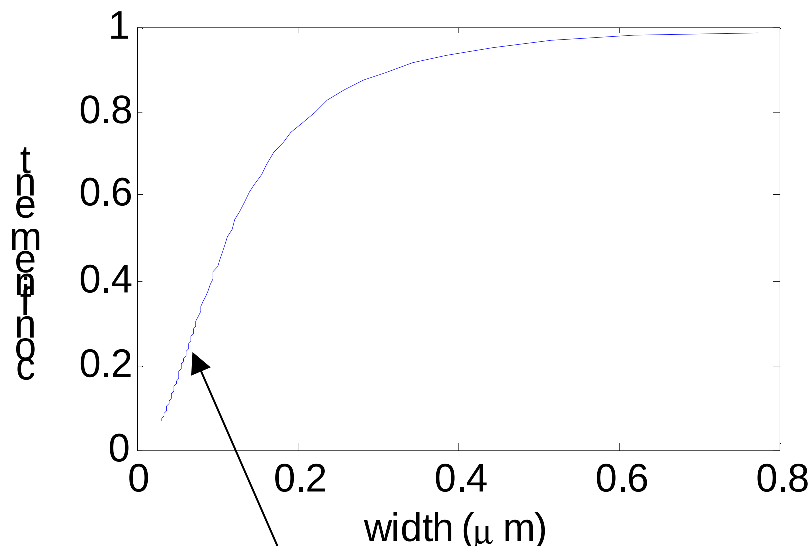
Development of Low-loss Waveguides Architectural Considerations

Single deeply-etched InP/InGaAsP rib waveguide





Use of narrow ridge increases percentage of modal propagation outside of lossy InP material (α~1 cm^{-1})

Decrease of ridge width to 0.1 to 0.2 μm range decreases loss to approximately 0.1 cm^{-1}.

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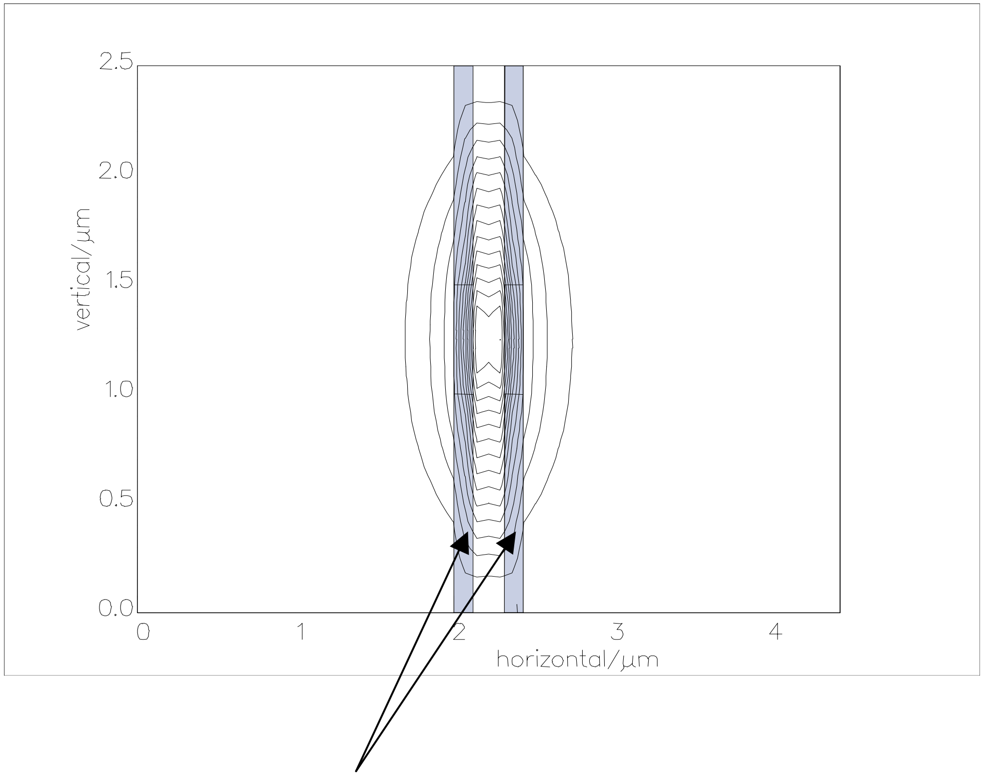
Development of Low-loss Waveguides Architectural Considerations (2)

Twin deeply-etched InP/InGaAsP rib waveguides

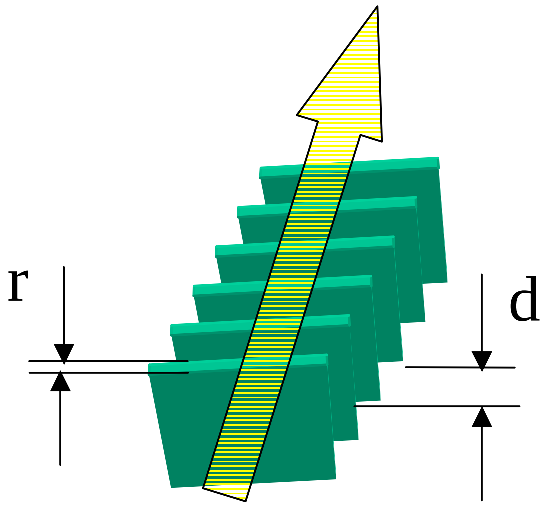


TM mode of twin waveguide structure with rib width of 0.12 µm, gap of 0.2 µm, and overlap of 0.25. Estimated loss would be 0.1 cm^{-1}.

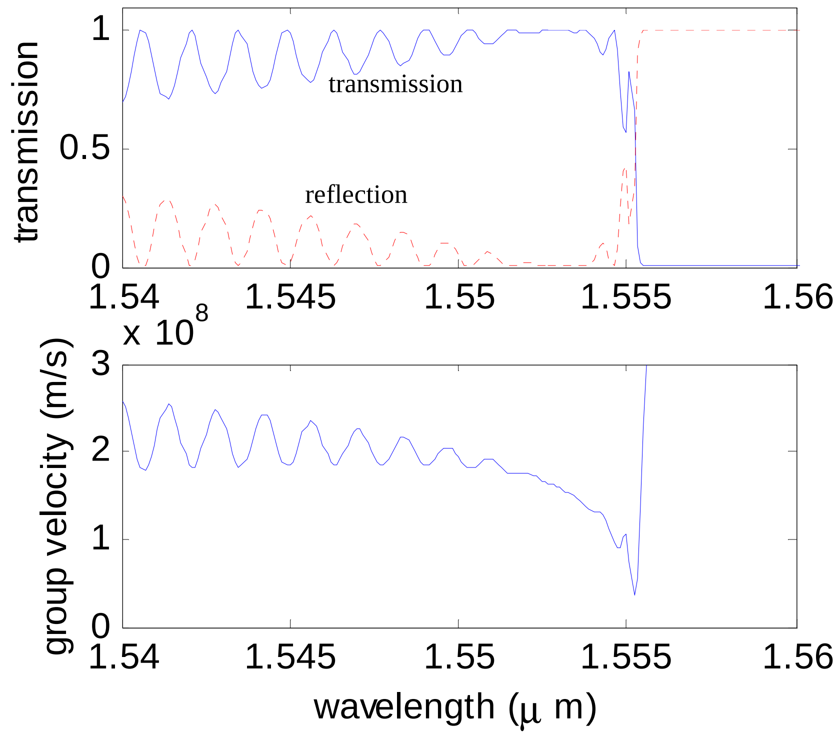
Use of twin narrow ridges confines majority of mode to outside of InP ribs.

Development of Low-loss Waveguides Architectural Considerations (3)

1-D photonic crystal slab rib waveguide



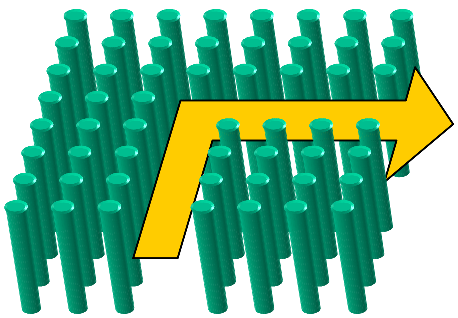
Further reduction of material overlap by forming 1-D photonic crystal structure.

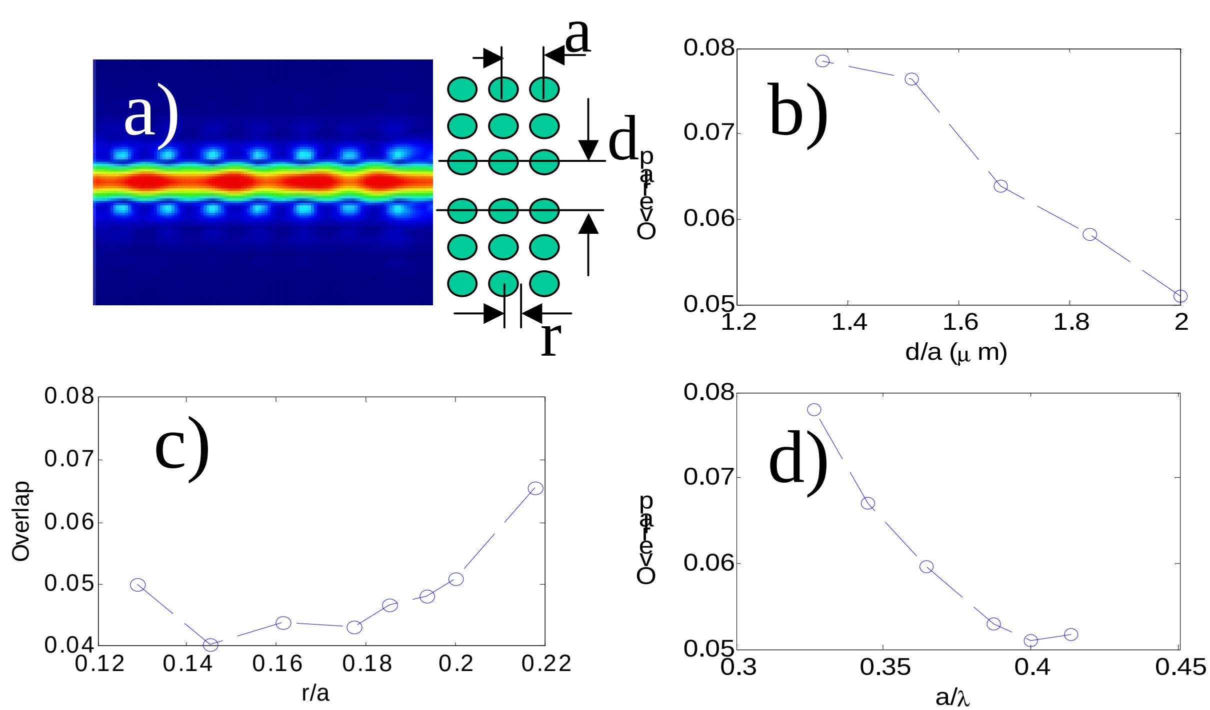


For λ=1.552 to 1.553 μm, losses are reduced to <0.1 cm^{-1}.

Development of Low-loss Waveguides
Architectural Considerations (4)

2-D photonic crystal "airguide"





Ability to achieve extremely low material overlap, 0.05, with proper lattice (a), post radius (r), and airguide width (d). Model shows good design tolerance to achieve loss <<0.1cm^{-1}.

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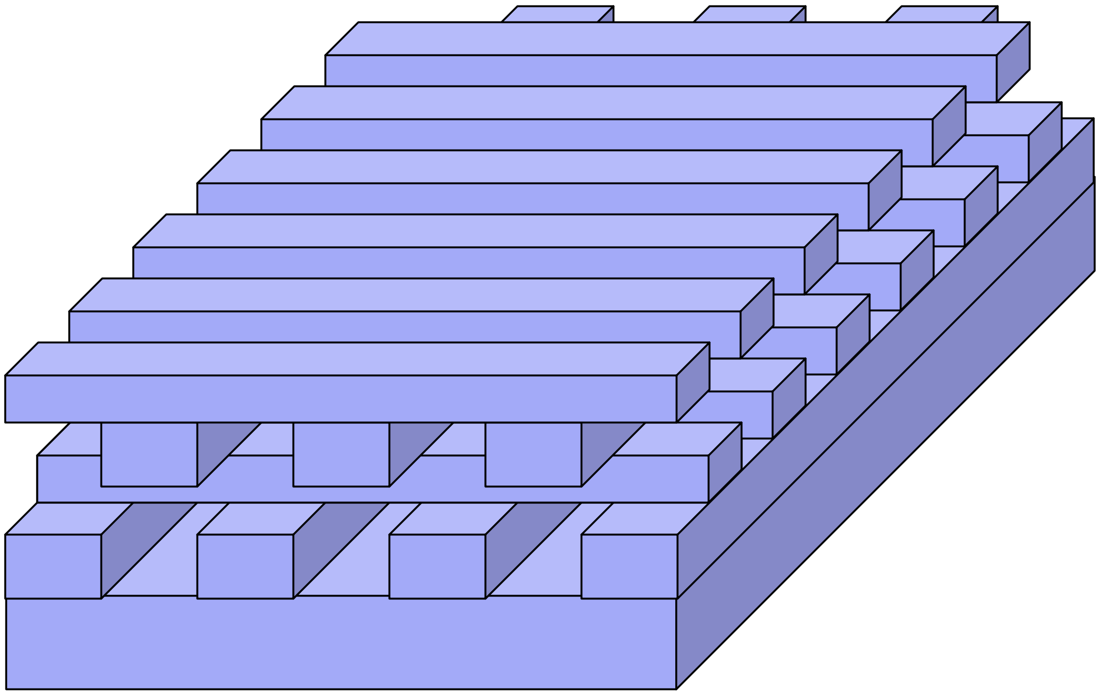
Development of Low-loss Waveguides Architectural Considerations (5)

3-D photonic crystal "airguide"



- Developed using InP/InGaAsP or InAlAs regrowth technology.
- No use of complex wafer bonding techniques.
- Forms full 3-D photonic "woodpile" structure for complete modal confinement

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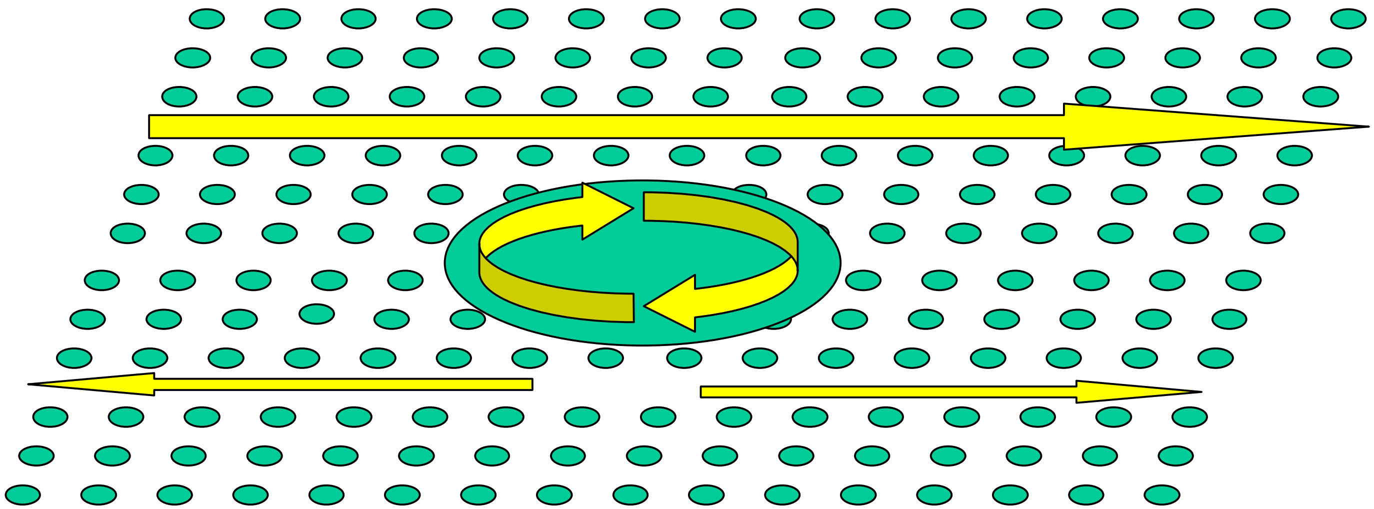
Resonant Defect Coupling for Delay Taps



Resonant coupler acts as photonic crystal defect. Coupling can be tuned by use of the electro-optic effect.

Technical Challenges

- Reduction of sidewall roughness in low-dimensional photonic structures.
- Vertical mode confinement in 1-D and 2-D waveguide structures.
- Tunability of resonant taps.
- Testing of sub-micron structures.
- Uniformity of resonant taps across 1 cm^2 sample.

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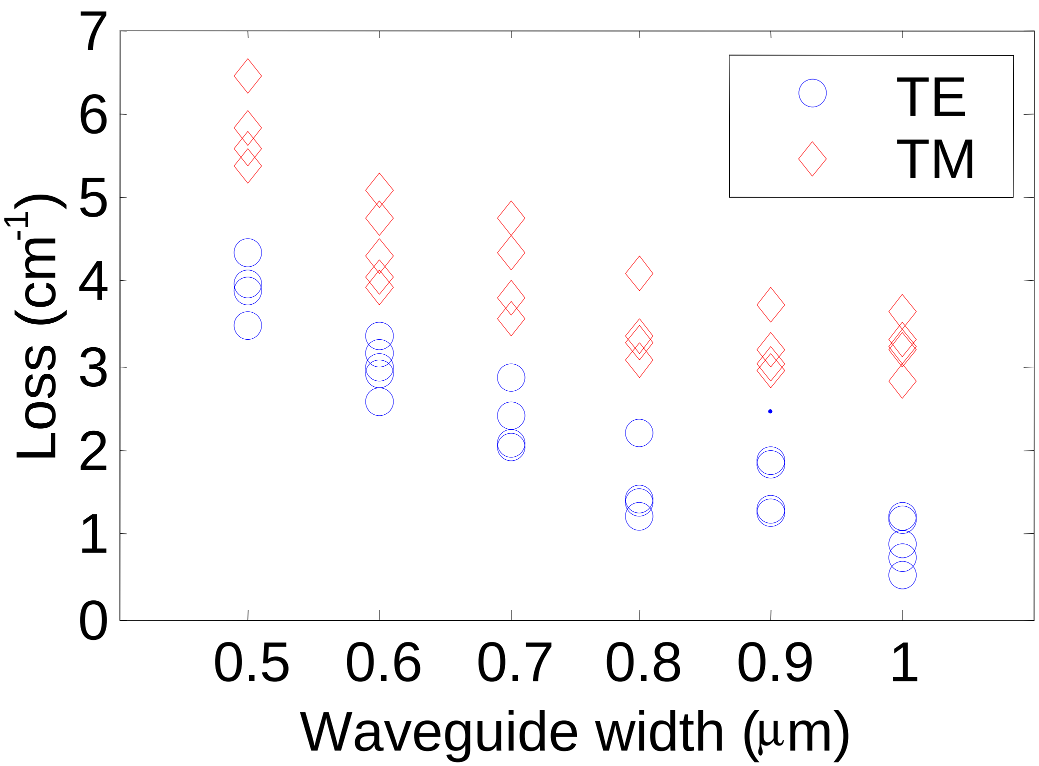
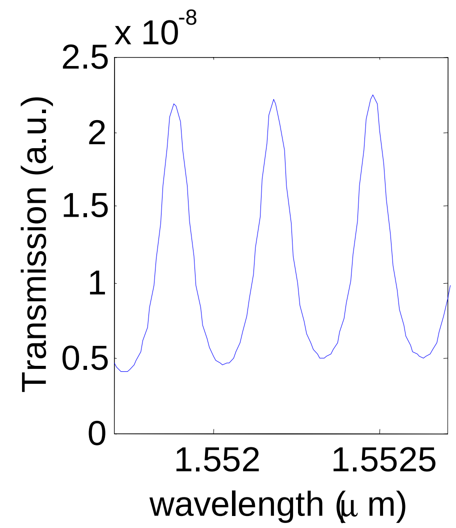
Preliminary Accomplishments

World record low-loss InP-waveguides





4 cm^{-1} for 0.5 μm width x 4 μm depth waveguide!

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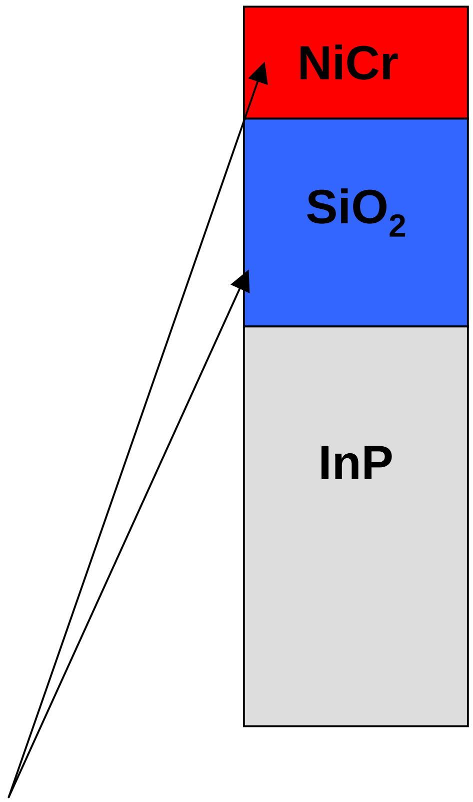
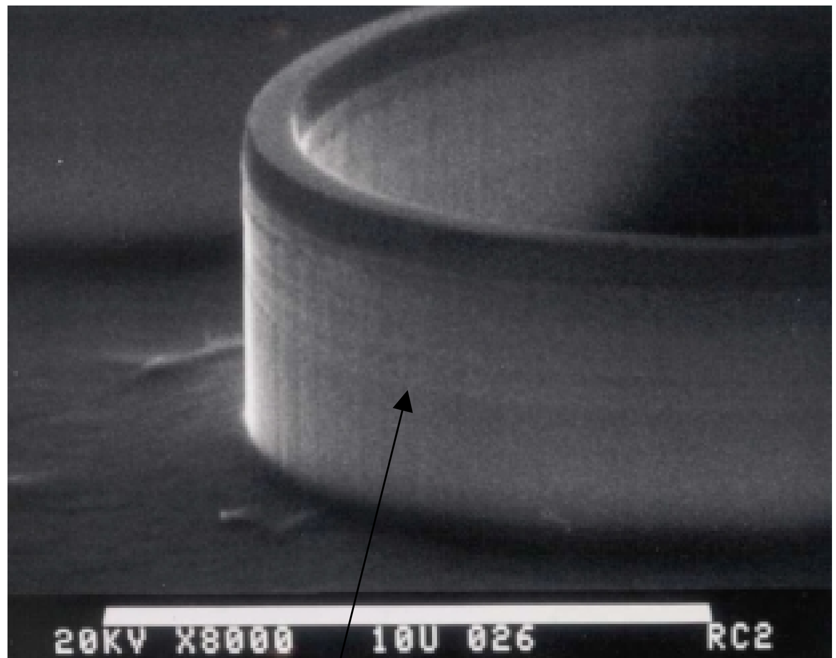
Preliminary Accomplishments(2)

Ultra-smooth, high verticality etching of InP-based ring resonators.





Bilayer mask to prevent erosion and reduce grain size.

Estimated rms sidewall roughness <λ/20, achieved by $Cl_2/H_2/Ar$ ICP-RIE. Developed under DARPA-RFLICS program.

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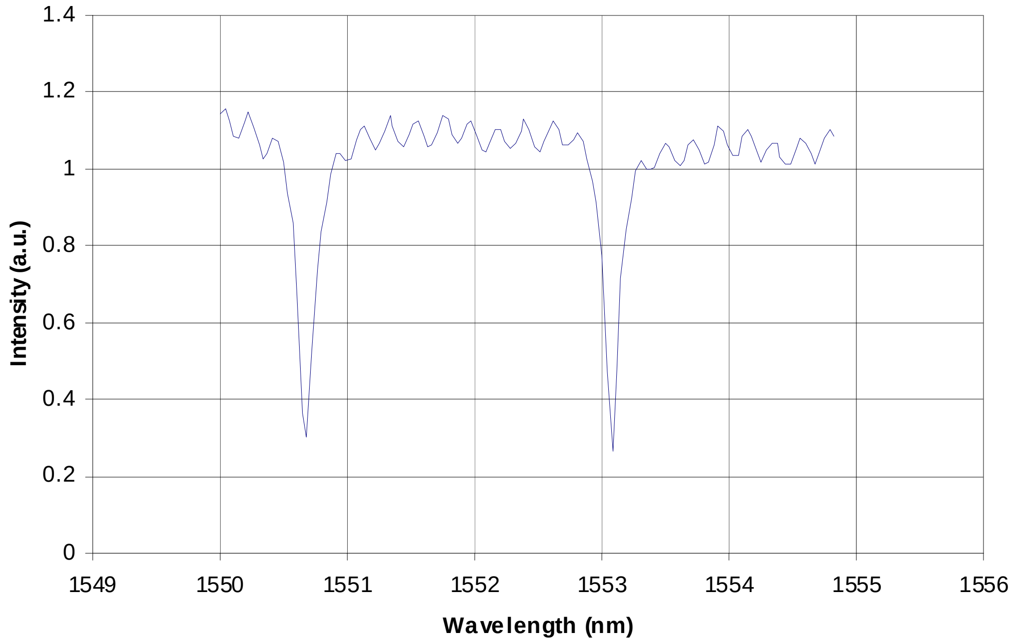
Preliminary Accomplishments(3)

High Q ring resonators



Achieved Q>10^4 on DARPA RFLICS Program

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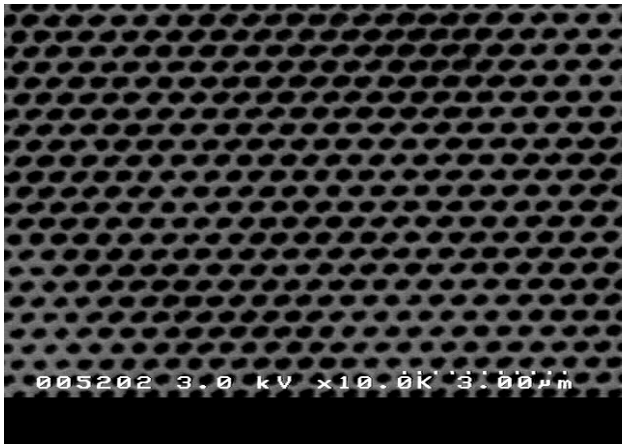
Preliminary Accomplishments(4)

Development of InP-based 2-D photonic crystal structures



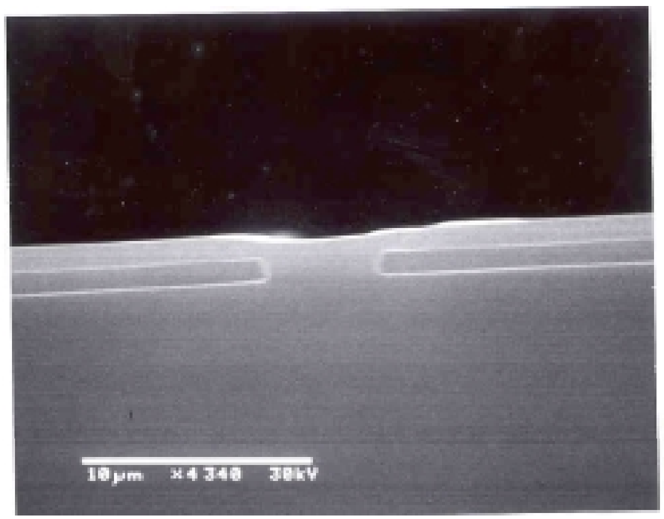
- 0.6 µm deep InP holes
- 0.15 µm radius
- 0.45 µm lattice spacing

Formation of InP"airguide" structure by dual holographic exposure and CH_4-based RIE.

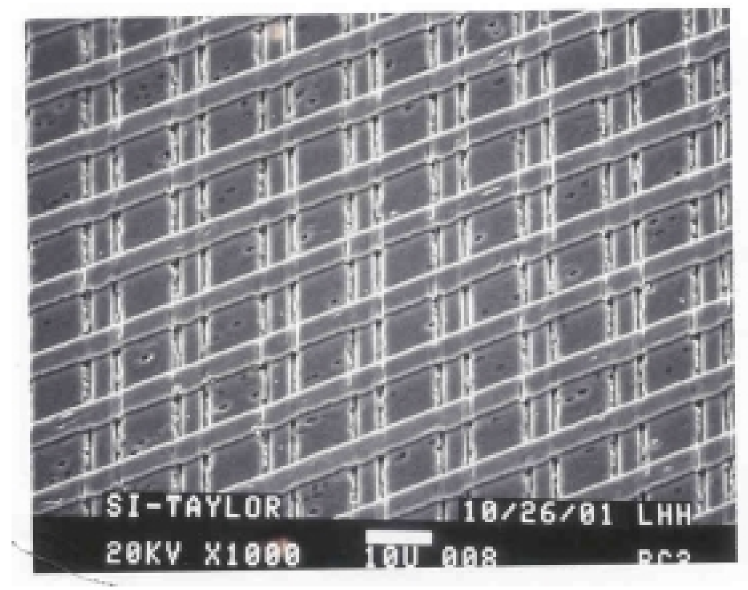
Formation of InP triangular hole lattice by direct write e-beam lithography and CH_4-based RIE.

Preliminary Accomplishments(5)

Development of 3-D InP "woodpile" structure



Establishment of InP/InAlAs regrowth to form base layers of 3-D woodpile.



Construction of InAlAs/InP layers.

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Year 1 Activity

- **Development of low-loss InP-based waveguides based on rib or photonic crystal structures.**
- **Development of photonic crystal structure models and waveguide design for optimum reduction in loss.**
- **Design and fabrication of high-Q ($>10^6$) microring resonators.**
- **Fabrication of high-Q resonant filter arrays.**
- **Demo of high-Q filter arrays.**

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SWAODL Program Plan